HUMAN AND AUTOMATION: A MATTER OF COOPERATION

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1. INTRODUCTION

The typical engineer's dream is designing a machine that will not have to interact with a human. If it is a nightmare, it presents an ordinary human who looks like unintelligent and prone to errors, which are more often than not unforgivable violations. Conversely, the typical ergonomist's dream is designing work situations where the humans can do everything they want without any constraints, interpreted as workload and intolerable knowledge requirements. The first dream — the engineer's one — is a caricature of machine centred design, and the second — the ergonomist's one — is a caricature of human centred design. As usual, the truth is in between that tries to reach a design conception centred on the Human-Machine System (HMS).

The notion of HMS is very old in ergonomics (e.g., Chapanis, 1965). Nevertheless it has been sometimes forgotten and sometimes retrieved. Its benefit consists in putting the "system" at the right place, not exclusively on the machine side but surrounding the two kinds of component — human and machine. Adopting this systemic point of view enables the designer to consider a task that is performed by the overall HMS, before defining the subtasks or functions allocated to each component. This kind of approach was re-activated slightly more than twenty years ago by E. Hollnagel and D.D. Woods (1983) who introduced the notion of *Joint Cognitive System* within the context of cognitive ergonomics and cognitive engineering, the former dealing with the role of the human, the latter with the role of the machine in the HMS. Human scientists like E. Hutchins in his studies on airline cockpits have very well defended such a position. The Hutchins' expression (1995) "*How a cockpit remember its speed?*" is a good illustration of the importance of the HMS notion. In this particular case, what is crucial is the fact that the cockpit must memorise its speed, before choosing the particular location of the memory within the HMS, in the pilot's head, in the computer silicon, or both. As a matter of fact, redundancy between the human and the machine is often a design quality criterion, especially in order to insure mutual control between the two agents, or dynamic task allocation, for example in the case of unavailability of one of the agents.

People working within the industrial or transportation domains more often use the word "machine", with a reference to cybernetics, whereas those who are working in close interaction with computer science are obviously prone to use the word "computer". Because the first studies on human-machine interaction have mainly concerned computers, the terminology adopted for this domain is Human-Computer Interaction (HCI), associated to several well-known conferences. However, this difference in terminology should not mask an essential distinction between two types of situation where HMS can be encountered — static and dynamic situations (Hoc, 1993).

HCI studies have been mainly devoted to static situations for which computer science has developed various products. The static feature of a situation is defined from the HMS point of view. It is related to the fact that the HMS fully controls the situation. In other words, no modification can appear in the situation without being produced by the HMS itself. Typical examples can be found in clerical work. Computer science, as well as cognitive ergonomics or psychology of problem solving, have very often focused on static situations. It is the kingdom of "computerization".

With the introduction of new technology in the factory, the aircraft, the train, the car, etc., another kingdom has been opened, that of "automatization", in relation to automation, rather than computer. A huge amount of research effort has been devoted to the relation between human and automation, especially within the community organised at the meeting point between cognitive ergonomics, cognitive engineering and human engineering. Although the term has unfortunately felt into disuse, this research trend is more related to cybernetics — the science of dynamic systems, whatever their natural or artificial nature. It is mainly concerned by dynamic situations, from the HMS point of view in that the HMS controls the situation only partially. The HMS actions are combined with other factors that are hidden or unexpected. In other words the HMS actions are not sufficient to fully determine what happens.

Confronted with the increasing development of automation within the dynamic situations, the HCI domain has been progressively enlarging in order to integrate the two kinds of situation. In the following, I will concentrate myself on the dynamic situations and argue that the development of more and more “intelligent” automation leads to enrich the notion of interaction by adopting the cooperation point of view. If one considers that intelligence is the capability of a cognitive agent to adapt to novel situations, strictly speaking machine intelligence has been rapidly increasing for several tens of years. Besides, intelligence is not only a property of computer science products, but also a property of automation. The increasing intelligence of automatic devices enables them to be autonomous. This has led some engineers to dream of a full automated world. Nevertheless, the optimisation of a HMS is far from being systematically found in a suppression of the human component. Even apparently fully automated the French underground VAL (in Lille, Rennes, and Toulouse) does not work when there is a strike! Obviously, the first product of intelligent automation is the design of almost autonomous devices that have the status of cognitive agents with which humans must deal. Human and artificial agents cooperate de facto, in the strict and minimal sense of operating together within the same environment, that of the HMS. We will see later that a stronger sense should be given to cooperation.

The relations between human and automation have been studied for a long time. Some of these approaches are of interest in order to introduce the cooperation topic, those that deal with the consequences of function allocation between the human and the machine. We will restrict ourselves on one of the well-known approach to this problem, because it has inspired recent experimental studies within the domain. It was the Sheridan’s approach of Levels Of Automation (LOA: Sheridan & Verplanck, 1978). After stressing the limits of this kind of approach, as well as its interest, we will justify the introduction of a functional point of view of cooperation, going beyond the sole function allocation problem. Then, we will describe three Levels Of Cooperation (LOC) in terms of cooperative activities, added to the private activities, that is to say in terms very different from LOA. And LOA will be replaced by a typology of cooperative situations in terms of Modes Of Cooperation (MOC). Finally, some implications of this cooperation point of view will be delineated, from a theoretical as well practical point of view. This presentation will be illustrated by some examples coming from our own studies on air-traffic control and car driving support.

2. LEVELS OF AUTOMATION

The Sheridan’s LOA typology (Sheridan & Verplanck, 1978) describes the full range of automation, from fully manual control to fully automated control. The intermediary steps are formulated in terms of symbolic information processing from supporting solution generation to supporting solution execution. Some examples of steps are the following.

- The machine proposes alternatives among which the human must make a choice and execute (decision support with weak guidance).
- The machine suggests a particular alternative, which the human will implement (decision support with strong guidance).
- The machine suggests a particular alternative, which the human approves before the execution by the machine (decision and implementation support).
- The machine makes the decision, implements it, and let the human informed afterwards (human supervision).

This approach has generated several studies, which cannot be accounted in detail. For example, Endsley and Kaber (1999) have found that the HMS performance is improved when the machine provides the human with an implementation support, but only in normal situations. During automation malfunction periods, the human deprivation of implementation is not beneficial to performance. This kind of result is very often interpreted as a “human out of the loop” phenomenon leading to complacency (negligence of supervision of the delegated function) and loss of situation awareness. The same authors (Kaber & Endsley, 2004) have suggested that Adaptive Automation, using a dynamic function allocation principle, should be a way to fight against the undesired phenomenon.

LOA essentially explains the function allocation from an engineering perspective — a machine centred one — without reference to the cognitive processes provoked in the human by the LOA. For example, what could be the effect of proposing alternatives? Would the human have time to choose among them? Would not the human systematically take the first alternative that is proposed? In order to answer these kinds of question, we need a model of the interaction processes between the human and the machine. We will see later than these processes can be considered as cooperative activities. Another limitation of the LOA approach in its genuine presentation is its restriction to symbolic information processing. In cognitive science, the term symbolic qualifies information that is not restricted to its physical features when it is processed. A good example is given by language and any kinds of codes behind which the meaning is processed rather than what is perceived. From a psychological point of view, symbolic activities are costly, must be executed sequentially, step by step, and so on. In order to enable low costs and parallelism, the humans develop routines by doing. These routines are sub-symbolic in that they can process the surface features of information without needing to access to the meaning. For example, at the beginning, traffic lights are processed as symbolic information, red meaning that we must stop, green that we may go ahead. After experience, the driver can react to the colour without processing its meaning, for example starting after perceiving a green flash, like a chemist's green cross.

This limitation to symbolic activities is not the specificity of LOA, it is also currently found in various approaches of cooperation. That is why, trying to enrich the LOA framework by the cooperation one, we will also try to cover the two kinds of process, symbolic as well as sub-symbolic activities. This covering is much more justified when studying human-automation than traditional human-computer interaction. As a matter of fact, a large part of dynamic situations covers sensori-motor activities without direct implication of symbolic control (e.g., car trajectory control). However, the two kinds of activity are always operating in parallel and in interaction, symbolic control supervising sub-symbolic control and sub-symbolic control returning information (emergence) to symbolic control (Hoc & Amalberti, in press).

3. A FUNCTIONAL APPROACH TO COOPERATION

The framework proposed by Hoc (2001) is based on a functional rather than structural approach and is not aimed at describing relational structures between cooperative agents, such as distribution of authority (Millot & Mandiau, 1995) or competencies (Schmidt, 1991) between agents. Its main objectives are to identify, analyse, implement and support cooperative activities. These activities are considered to be additional to private activities when moving from an isolated individual activity to a collective activity. For example, function allocation is a cooperative activity and would be unnecessary if an agent was working alone.

The framework proposes that cooperation is an activity of interference management between non-independent tasks distributed among several agents. In line with Castelfranchi (1998), interference can be considered both as positive and negative. It reflects the fact that the goal of one particular agent has something to do with that of another agent, and each can either facilitate or disrupt the other. Interference is managed in order to facilitate the individual tasks or the collective task as it stands. Cooperation does not always imply a perfect symmetry between the diverse agents. Sometimes there are strong reasons for giving priority to the facilitation of one particular agent's task. For example, in-car human-machine cooperation is supposed to give priority to the driver's task (at least in normal circumstances).

In order to manage interference, the framework decomposes the cooperative activities involved into three levels. The first level is cooperation in action where the cooperation activity is directly related to action and corresponds to a local, concrete, and short-term interference. The second level is cooperation in planning where the cooperation activity is more remote from the concrete action and aims at maintaining a COmmon Frame Of Reference (COFOR) between the agents. The third level is meta-cooperation and consists in maintaining long-term models of oneself and of the partner, on the basis of training and experience. Thus, the levels are distributed along two confounded dimensions. The first one is the distance from the immediate action, in terms of abstraction. The second one is the temporal horizon covered by the cooperative activity.

4. LEVELS OF COOPERATION

4.1. ACTION LEVEL

At the action level, interference management is restricted to the short term, with minimal anticipation of the agents' goals. The positive or negative features of interference are highly relative to their products in terms of performance. Interference occurs when the tasks are not independent. This means that the tasks can be, for example, in precondition relations (one being necessary to perform another one), in interaction relations (the two being performed simultaneously), or in redundancy relations (the same goal can be reached by any of the agents). Interference can take the form of mutual control when an agent checks another agent's activity to give back an evaluation (e.g., a warning). So, interference is not always negative, it can be deliberately instigated to improve effectiveness. After its appearance at the action level, interference can also trigger cooperative activities at the other cooperation levels (e.g., common plan elaboration in order to resolve interference on a longer term basis).

In a simulator study of cooperation between two air-traffic radar controllers, cooperation in action has been positively evaluated (Hoc & Carlier, 2002). The main aim of this experiment was identifying the cooperation skill to be integrated in an automatic conflict resolution device. One third of the cooperation activities at this level consisted in mutual control between the two controllers. And another one third was devoted to communications aiming at making easier the anticipation of the partner's imminent goal. Negative aspects of cooperation in action only concerned one third of the cooperative activities in action (detection and resolution of unanticipated interference. A possible explanation of this efficient cooperation in action was the adequate maintenance of a common frame of reference between the partners (see below).

The removal of interference during the course of action can be considered as a means of reducing workload. The other levels of cooperative activities, because of their ability to abstract and to anticipate, are likely to restrict interference in action, that is to say to resolve it beforehand. However, the cooperative activities, at whatever level, are also a means of adapting to unforeseen situations, and so interference is sometimes desirable. For instance, mutual control is recommended in aircraft cockpits because every possible error produced by a complex interaction between the agent, the machine and the situational context, cannot be anticipated (Wiener, Kanki, & Helmreich, 1993). Initial (pre-task) planning in order to render the diverse agents' tasks independent (and hence minimise interference) thus has a limited validity. Some workload cost (in terms of real time interference management) must therefore be paid to gain adaptation power.

4.2. PLAN LEVEL

At the plan level, interference is managed at a more abstract and anticipative level, and depends on the elaboration and maintenance of a common frame of reference (COFOR). Roughly, a COFOR is composed of shared representations (between the agents), which help to facilitate the activities situated at the action level. In fact, these representations are complementary rather than identical – that is to say different but non-contradictory. It is a common fact in ergonomics that each agent must be assisted by external representations that are presented in a suitable format for this particular agent's action. Thus, the same "abstract" information must be presented differently to several agents in relation to their own tasks.

COFOR does not only include representations of the environment (team situation awareness), but also of the team's activity (e.g., common plans and goals, function allocation, etc.). It is easy to create conditions for shared awareness of the external situation, although the information format must be suitable. On the other hand, it is much more difficult to maintain a shared representation of the team's activity or goals – for example, whether the machine can recognise the human's intentions. Communication between the agents in the system is a crucial component of developing and maintaining an effective COFOR. The humans must communicate their intent to the machine via their actions; the machine must similarly communicate its status and activities to the humans. Only through these clear and open communications can situation awareness be truly shared and the interaction optimised. Obviously, the automatic devices cannot be valid in any circumstances, especially because of the high environment complexity. A poor situation awareness can be the major cause of difficulty to return to manual control — a problem frequently mentioned in human-automation studies.

The importance of COFOR maintenance in cooperation has been stressed in the study of air-traffic control cited above (Hoc & Carlier, 2002). As a matter of fact, almost 80% of the cooperative activities consisted in maintaining or elaborating the COFOR. Almost the two thirds of the cooperative activities at this level aimed at maintaining or elaborating the part of the COFOR representing the team's activity as opposed to the external situation under control.

4.3. META LEVEL

At the meta level, the experience of cooperation within the team is exploited to facilitate the activities of the previous levels – for example, by using models of the other agents and of oneself. At this level, trust in automation and in one's relations with automation, together with self-confidence, can be calibrated through the use of models elaborated by experience (Lee & See, 2004; Muir, 1994). The lack of appropriate model of the machine can lead to an over-generalisation, so that the machine can be utilised outside its validity domain. Last, but not the least, an inappropriate machine model can lead to automation surprises, which have been well documented in the aviation domain (Funk et al., 1999; Sarter & Woods, 1992).

In a study of the use of an active steering device, automatically assuming the car lateral control function, the importance of this meta-level has been stressed (Hoc et al., 2006). At the beginning, more than 40% of the drivers' verbal reports denoting human-machine cooperation activities concerned the elaboration of models of the machine operation and of the human-machine interaction while performing the task.

5. MODES OF COOPERATION

5.1. PERCEPTIVE MODE

In the perceptive mode, the machine is utilised as an extension of the sensorial organs. In terms of engineering, this is the instrumented mode. Although the production of a physical measure is a well-defined task for an engineer, the usefulness of this measure for the human is questionable. Symbolic processing is serial and, therefore, very costly in terms of attentional resources. In addition, the information that is processed is discrete and not continuous, and this is not compatible with smoothness of action. In any case, the perception mode must be considered as a cooperation mode since it is designed to interfere with the human's activity. It is mainly a question of choosing the best human-machine interface, either in terms of an appropriate code (form/content) to support symbolic processing or an efficient sensorial modality to easily trigger action.

The distinction between symbolic and subsymbolic visual information has been stressed in a car-driving study of the effect of hazard road signs when approaching bends (Milleville, Hoc, & Jolly, in press). Road signs revealed an effect on symbolic information processing, triggered by explicit processing such as a verbal evaluation of hazard or of curvature. However, there was no effect on subsymbolic information processing, triggered by implicit processing underlying the concrete production of a steering wheel angle. More especially, the road signs did not reduce the well-known bias of high curvatures underestimation. In another fixed-base simulator study, Milleville (2006) has inserted black bands both on the top and the bottom of the windscreen, these bands being submitted to tilts in bends in relation to the virtual lateral acceleration. When the participants were not informed of this modification of the visual framework, analogue to what they could see in a real tilting car, reduced their speed. Thus, the subsymbolic processing of the visual information was efficient. However, when the participants were informed beforehand, not only this effect was not observed but the reverse. The participants increased their speed interpreting the information as an illusion without relation to safety.

5.2. MUTUAL CONTROL MODE

In the mutual control mode, the machine is designed in such a way that it can interpret information in terms of limits to be respected in relation to risk assessment. The concept of mutual control is very different from shared control, which simply denotes the fact that several agents control an external situation at the same time, but not necessarily each other. Thus, for example in car driving, a device can provide drivers with feedback on their actions (mutual control) in terms of exceeding limits. Three sub-modes can be envisioned, all with different degrees of invasiveness.

The warning mode and the action suggestion mode are restricted to (interpreted) information transfer, without any action taken on the vehicle itself. Here, warning is not taken in the sense of information provided on a technical state (e.g., a fault), but as a criticism of the human's actions. The warning mode has also been evaluated in critical situations while taking a bend in order to avoid lane departure. Suzuki and Jansson (2003) have shown that auditory warning and steering wheel vibration were efficient in reducing response time and maximum lateral deviation in critical situations, but only in comparison with other types of support and not with a control situation (without support). More recent experiments (Hoc et al., 2006; Navarro, Mars, Hoc, Boisliveau, & Vienne, 2006) have qualified this conclusion, in comparison with a control situation, on the basis of the delay in returning to the lane centre, showing that the mode (lateralised sound in the direction of the deviation and steering wheel vibration) might only be efficient within certain contexts. Especially, the effect of the warning was modulated by the driver's risk evaluation.

When the warning mode is present on a control (e.g., a pedal or wheel), by using the haptic modality it could become an action suggestion and, therefore, could be more effective in emergency situations, acting as motor priming. In the study cited above, Suzuki and Jansson (2003) have evaluated this kind of mode by means of the application of torque to the steering wheel. The results were not conclusive because, for some participants, the stimulation produced the opposite effect. Hoc et al. (2006) implemented the suggestion mode by an asymmetric vibration on the steering wheel, triggering a response in the appropriate direction. Although the effect was positive, it was not significant due to the fact that individual differences were greater than for the warning mode. In addition, the stress produced by a road departure was likely to mask the effect of the action suggestion, underlining the importance of context in determining mode effectiveness. However, Navarro et al. (2006) found a clear-cut effect of motor priming by an asymmetric vibration of the steering wheel suggesting turning toward the correct direction in a simulator study. The effect of motor priming was much greater than auditory or haptic warning mode. However, like the warning mode effect, the action suggestion mode effect was modulated by the driver's risk evaluation. Thus, in parallel with the direct (subsymbolic) effect of motor priming on action, there is a possible (symbolic) effect of diagnosis on the action level, capable of reducing or increasing the effect of motor priming. This result is important because triggering an irrepressible action in a wrong situation could create negative interference.

The limit mode, although under the driver's control, introduces more constraints, for example by creating pedal or wheel resistance. A fourth possibility (correction mode) would to let the driver go beyond the limit and then to make the required correction.

An appropriate COFOR between the machine and the human is crucial in order to sustain the mutual control mode.

5.3. FUNCTION DELEGATION MODE

The cooperation modes considered under the function delegation category go beyond simple mutual control. They correspond to a lasting function delegation from the human to the machine. In the mediatized mode, the machine takes a control as an order to be implemented using a procedure that covers a certain period of time. In the control mode, the machine controls a parameter, thus allowing the human to take charge of the others. There is also a need for an efficient COFOR maintenance. An extreme case is the fully automated mode. Within the limited framework of this paper it will not be discussed separately.

The function delegation mode has been widely studied in the literature on human and automation, as well as the full automation mode (see below). Several kinds of drawbacks of automation, when it interacts with humans, have been identified (Hoc, 2000; Parasuraman & Riley, 1997). Mainly four "automation biases" have been described.

- Loss of expertise due to the lack of exercise of the function delegated to the machine.
- Complacency, which could be interpreted as neglecting to gather information necessary to the function fulfilment, and/or neglecting to supervise the automated function, and/or neglecting to improve the performance of the automated function. This phenomenon has been identified in a study of cooperation between air-traffic controllers and an automatic conflict resolution device (Hoc & Lemoine, 1998). When the humans feel themselves responsible for the function allocation between them and the machine, they exert mutual control on the machine. In the opposite case, they are complacent and do not supervise the machine.
- Bad-calibrated trust due to the lack of an adequate model of the machine (or of the interaction).
- Loss of adaptability due to an insufficient feedback returned to the human (i.e., the best adaptive agent in the team), either on the machine operation or on the machine's situation awareness.

Loss of expertise, complacency, and loss of adaptability contribute to the well-known difficulty of returning to manual control. Designers very often underestimate this issue when they are too much focusing on the machine. Nevertheless any machine is designed to be efficient within a defined validity envelope. More often than not the human remains within the human-machine system in order to take the control when the situation leaves the envelope. In the study cited on active steering in car driving, Hoc et al. (2006) have interpreted the difficulty to return to manual control in relation to complacency, on the basis of a negligence of visual information needed for manual lateral control.

6. CONCLUSION

In the cognitive ergonomics literature, the description of the automation biases has been prominent for several tens of years. Some effort has been devoted to the understanding of the causes of these biases and some countermeasures have been suggested, like introducing unexpected periods of manual control (especially in the line of the work done by Kaber and Endsley, 2004). However, much work remains to be done in order to define efficient and ecological countermeasures. For example, it is not sure that the voluntary introduction of failures in a machine is ecologically acceptable… Some efficient solutions could be found within the human-machine cooperation framework.

First, we could introduce much more cooperation in action if we are able to reduce the cost and increase the effectiveness of the real time management of interference. Most of the time, designers consider human-machine interaction mainly at the symbolic information level. Indeed, engineers have symbolic representations of information to be transmitted to the humans and they are inclined to think that this kind of format is appropriate. However, a correct task analysis can prove that it is not true. Perceptual and sensorimotor interaction could be preferable in terms of efficiency. There are good examples of this benefit in car driving.

Second, the sensorimotor level could also be very useful as a tool for efficient communications between the human and the machine, resulting to COFOR maintenance at low cost. In the reverse direction, communication from the human to the machine is costly for the human. Thus, we need to provide the machine with some capability of diagnosing the human state. Some progress has recently been done within the car-driving support domain, for example in order to trigger collision avoidance device in the right time and advisedly (e.g., Bellet, 2006). This kind of research should be developed further. Improving communication between the agents' individual situation awareness is a way to improve the human-machine system's situation awareness. However, this does not prevent from erroneous representations and from conflict resolution.

Third, key to access to an appropriate trust in the machine and in the human-machine interaction is the elaboration by each partner of models of the others and of the interaction with the others. As machine intelligence, in terms of adaptive power, is growing, explicit teaching of appropriate models is absolutely necessary. This sets two questions: (a) the definition of simplified models, just sufficient for their purpose; (b) the design of efficient training. These questions are particularly crucial for consumer electronics or software.

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